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(54) Tool for and method of geological formation evaluation testing

(57) A geological formation tester tool (100) comprises a pulse generator (114), for generating a pulsed pressure waveform in a geological formation, wherein the pulsed pressure waveform is created about a first center frequency and wherein the pulse generator includes means for varying the center frequency at least one receiver probe (110), the or each receiver probe spaced apart a predetermined distance from the pulse generator and in contact with the geological formation; and at each receiver probe, a sensor (118) operably connected to the or each receiver probe for sensing a first arrival time at each receiver probe, of the pulsed pressure waveform.

A method of determining properties of a geological formation comprises: providing a downhole tool (100) having a pulse generator (114) and at least one receiver probe (110), the or each receiver probe spaced apart a predetermined distance from the pulse generator; generating a pulsed pressure waveform in the geological formation with the pulse generator; wherein the pulsed pressure waveform is created about a first center frequency and wherein the center frequency is variable sensing, at the receiver probe, a first arrival time of the pulsed pressure waveform; and determining the velocity of the pulsed pressure waveform.

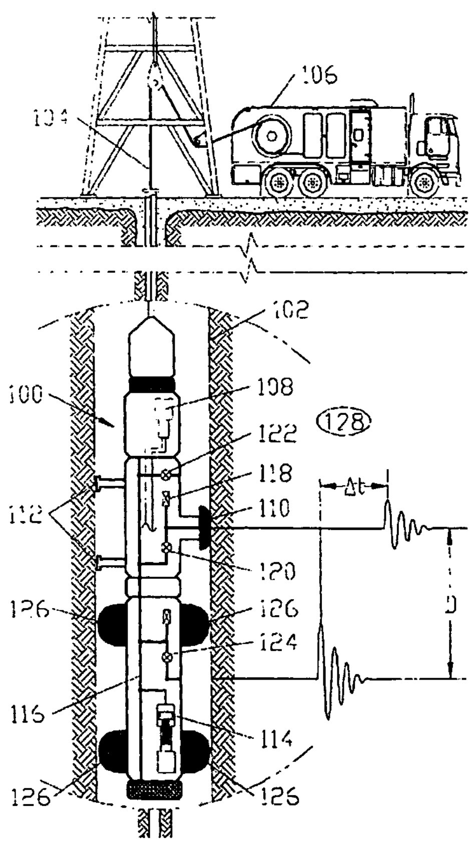


FIG. 1

EP 0 950 795 A2

Description

[0001] This invention relates to the field of measuring characteristics of earth formations penetrated by a borehole and, more particularly, relates to a tool for and method of formation evaluation testing using pressure pulse velocity.

[0002] The determination of permeability and other hydraulic properties of hydrocarbon-bearing formations surrounding boreholes is very useful in gauging the produceability of hydrocarbons in those formations. Permeability can be determined by taking and analysing core samples from the formation, but this is a difficult and lengthy process. Therefore, various methods have been developed for determining the permeability of a formation *in situ*.

[0003] In traditional formation tester systems, formation evaluation is based on interpreting tests using pressure drawdown and build up data. However, in low permeability formations, this approach requires lengthy test times.

[0004] Another technique for determining formation permeability is disclosed in US -A-5,672,819. This patent discloses the use of a formation tester piston (or "transmitter") operated at a continuous constant frequency. Amplitude and phase differences are obtained between the tester piston and a second probe (or "receiver"), permeability being inferred using a phase delay analysis approach. However, there are some disadvantages in the phase delay approach. For example, in low permeability formations, large delays (exceeding 360 degrees) may be encountered, leading to phase wrapping ambiguities well known in geophysics when phase information is used to infer rock properties. If amplitude information is used, the amplitude signal due to permeability is often "buried" in the amplitude drop due to geometric spreading. These problems have well known counterparts in resistivity tool design.

[0005] Earlougher, in "Advances in Well Test Analysis", pp. 111-118, Society of Petroleum Engineers, Richardson, Texas 1977, describes applications where a series of short duration pressure pulses are created at production wells and monitored at observation wells. In particular, velocity measurements are made, and from these, formation properties are determined using interpretation charts developed from "cylindrical" flow mathematical models of the transient Darcy flow.

[0006] Accordingly, it would be an advancement in the art to provide a formation tester system for evaluating formation properties, but for the "spherical flows" encountered in formation tester tool applications, especially for low permeability formations, without the problems inherent in phase delay approaches or the use of amplitude signals.

[0007] According to one aspect of the present invention there is provided a method of determining properties of a geological formation which method comprises: providing downhole a tool having a pulse generator and at least one receiver probe the or each receiver probe being spaced apart a predetermined distance from the pulse generator; generating a pulsed pressure waveform in the geological formation with the pulse generator, wherein the pulsed pressure waveform is created about a first center frequency; sensing, at a receiver probe, a first arrival time of the pulsed pressure waveform; and determining the velocity of the pulsed pressure waveform.

[0008] According to a further aspect of the present invention there is provided a geological formation tester tool comprising: a pulse generator for generating a pulsed pressure waveform in a geological formation wherein the pulsed pressure waveform is created about a first center frequency; at least one, receiver probe the or each receiver probe being spaced apart a predetermined distance from the pulse generator and in contact with the geological formation; and a sensor operably connected to the, or each receiver probe, for sensing a first arrival time at each receiver probe, of the pulsed pressure waveform.

[0009] The present invention provides a method and apparatus for testing geological formations using a pulsed pressure waveform created about a center frequency, preferably, a short duration sinusoidal pressure wave. A downhole tool is provided including a pulse generator, for example, a formation tester reciprocating piston, and a receiver probe. The receiver probe is spaced apart a predetermined distance from the pulse generator and is, for instance, in contact with the geological formation. The pulse generator (or transmitter) generates a pulsed pressure waveform in the geological formation. The pulsed pressure waveform is created about a center frequency. A first arrival time of the pulsed pressure waveform is sensed by a sensor operably connected to the receiver probe and includes, for example, a high accuracy quartz gauge. The velocity of the pulsed pressure waveform is then determined. The velocity of the pulsed pressure waveform is used to determine permeability, porosity, and compressibility of the geological formation and to determine viscosity of fluids in the geological formation. The center frequency is, preferably, increased to allow high resolution shallow depths of investigation of the geological formation and decreased to allow deeper depths of investigation with lower resolution of the geological formation.

[0010] In another embodiment of the present invention, a transmitter probe, operably connected to the pulse generator and in contact with the geological formation, transmits the pulsed pressure waveform to the geological formation. As in the first embodiment the first arrival time of the pulsed pressure waveform is sensed by a sensor operably connected to the receiver probe. In still another embodiment, more than one receiver probe and sensor is used on the downhole tool to observe more than one arrival time at different spacings or azimuthal orientations in the borehole.

[0011] The method and apparatus of the present in-

vention provides a simple system for the testing of a geological formation *in situ* and is especially advantageous in formations having a low permeability.

[0012] The present invention may be better understood and its numerous objects, features, and advantages made apparent to those skilled in the art by referencing the accompanying drawings.

Figure 1 is a schematic illustration of a first embodiment of the present invention;

Figure 2 is a schematic illustration of a second embodiment of the present invention wherein a transmitter probe is operably connected to a reciprocating piston;

Figure 3 is a schematic illustration of a third embodiment of the present invention wherein the downhole tool includes more than one received probe; and

Figure 4 is a chart illustrating group velocity, for example, in the present invention, as a function of formation permeability and transmitter excitation frequency.

[0013] The use of the same reference symbols in different drawings indicates similar or identical items.

[0014] With reference to Figure 1, a downhole tool 100 according to the present invention is lowered into a borehole 102, for example, by a cable 104 connected to a truck 106. Various types of downhole tool testing apparatus are well known in the art as well as various deployment methods, such as wireline or drillpipe deployment. The apparatus of the present invention is positioned in the borehole and deployed in the same manner. The apparatus of the present invention may also be permanently affixed within the borehole or be movable for a continuous measurement over a depth interval. An electrical motor or electrohydraulic system 108 powers the other components in the downhole tool 100. Electrical power to operate the downhole tool is transmitted through cable 104.

[0015] In a preferred embodiment, the downhole tool 100 includes a receiver probe 110 and backup pads 112 which are, for example, extended from the downhole tool 100 in order to engage the walls of the borehole 102. Engagement of the receiver probe 110 with the wall of the borehole 102 is necessary to isolate the receiver probe 110 from fluids contained in the borehole 102. Backup pads 112 are used to stabilize the downhole tool 100 and insure that the receiver probe 110 remains in place against the wall of the borehole 102.

[0016] The receiver probe 110 is spaced apart a predetermined distance from a reciprocating piston 114 (or transmitter), preferably in a range of about one-half to ten feet. (0.15 to 3m). The reciprocating piston 114 controls the pressure and flow rate at the receiver probe 110. The piston 114 is hydraulically connected to flow line tubing of the tool 116. Valve 124 is opened to allow communication of the pressure pulse to an opening between the packers. The piston 114 is designed such that it can generate a pressure pulse and therefore operate as a pulse generator. Packers 126 are used to isolate and center the pressure pulse between the packers within the borehole 102.

[0017] A sensor 118 including, for example, a high accuracy quartz gauge, is connected to the receiver probe 110 and is used to record the pressure at the receiver probe 110. The receiver probe 110 can be isolated from the piston 114 by isolation valve 120 and the piston 114 is isolated from the borehole fluids by isolation valve 124. An equalization valve 122 allows borehole fluids to enter flow line tubing 116 when testing is completed.

[0018] The downhole tool 100 is, for example, lowered into the borehole 102 on cable 104 from the truck 106. The electrical motor or eletrohydraulic system 108 then causes the receiver probe 110 and backup pads 112 to be extended such that they engage the borehole walls. The electrical motor or eletrohydraulic system 108 also causes the packers 126 to extend by inflating, which isolates an interval of formation between the packers 126. The piston 114 is used as a pulse generator to pulse the borehole fluids trapped between the packers 126 which immediately generates a pressure pulse in the formation adjacent to this section of the borehole.

[0019] The isolation valves 120 and 124, respectively, and equalization valve 122 are normally open as the downhole tool 100 is lowered in the borehole 102. Prior to setting the tool, valves 120, 122 and 124 are closed to isolate the flow line 116 from wellbore fluids. The isolation valve 120 is then opened and the piston 114 withdraws a small volume of fluid from the received probe 110 to create a drawdown that is recorded by the pressure gauge sensor 118. Preferably, the drawdown is about five to ten cubic centimetres of fluid. Isolation valve 120 is then closed, creating a buildup of pressure at the receiver probe 110. The pressure drawdowns and buildups are performed to insure that the receiver probe 110 is in hydraulic communication with the formation 128.

[0020] Isolation valve 124 is then opened and the piston 114 withdraws a larger volume of fluid, about 10 to 100 cubic centimetres from the borehole 102. Valve 124 is then closed and the pressure is allowed to build up. Valve 124 is again opened and piston 114 displaced to produce a short duration pulsed pressure waveform, for example, a pulsed well transient consisting of a short duration sinusoidal pressure waveform. The short duration sinusoidal pressure wave may be from about four to about ten cycles of the center frequency. The pulsed pressure waveform propagates through the geological formation 128. The sensor 118 senses a first arrival time (Δt) of the pulsed pressure waveform at the receiver probe 110. By using the distance (D) of the receiver probe 110 from the piston 114 and the transmitter-to-receiver transit time Δt of the pulsed pressure waveform to determine pressure pulse velocity, an accurate esti-

mate of permeability and other properties of the geological formation can be made using the velocity relationship below for group velocity.

[0021] The short duration pulsed pressure waveform is created about a center frequency. Once the pulsed pressure waveform is generated, it propagates through the geological formation with a "group velocity" (the velocity of energy propagation for wave-like disturbances). The group velocity (C_g) is calculated as follows:

$$C_g = \sqrt{\{8k\omega/(\phi\mu c)\}}$$

wherein:

k is the permeability of the geological formation,
ω is the circular frequency,
φ is the porosity of the geological formation,
μ is the viscosity of fluids in the geological formation, and
c is the compressibility of the fluids in the geological formation.

[0022] The circular frequency ω is calculated as follows:

$$\omega = 2\pi f$$

wherein f is the center frequency of the waveform in hertz.

[0023] For a pulsed waveform created about a centre frequency, the corresponding group velocity will be constant. The velocity of the pulsed pressure waveform is calculated by using the distance (D) of the receiver probe 110 from the pulse generator (shown herein as reciprocating piston 114), and the first arrival time (Δt) at the receiver probe 110 of the pulsed pressure waveform. The velocity of the pulsed pressure waveform is identical to the group velocity (C_g) as follows:

$$D/\Delta t = C_g$$

wherein a mechanism for determining formation properties is provided. Any of the four parameters or formation properties described previously can be used to determine the other three parameters. The center frequency can also be varied and multiple regressions performed to determine all four formation parameters. For example, the center frequency can be increased to study shallow depths of investigation at higher resolution in the geological formation, and decreased to study deeper depths of investigation in the geological formation at lower resolution.

[0024] Figure 2 illustrates a second preferred embodiment of the apparatus of the present invention, wherein downhole tool 200 is essentially identical the downhole tool 100 of Figure 1, except for the addition of a transmitter probe 202 and the absence of packers 126. The transmitter probe 202 is operably connected to the reciprocating piston 114 and transmits the pulsed pressure waveform to the geological formation 128. The transmitter probe 202 is preferably, positioned within the same azimuthal angle as the receiver probe 110 and is in contact with the wall of the borehole 102 to isolate the transmitter probe 202 from the borehole fluids. The receiver probe 110 and the transmitter probe 202 are spaced about one half to ten feet (0.15 to 3m) apart.

[0025] Figure 3 illustrates a third embodiment of the apparatus of the present invention, wherein downhole tool 300 is essentially identical to the downhole tool 200 of Figure 2, except for the addition of a second receiver probe 302, and corresponding isolation valve 304 and sensor 306. More than one receiver probe can be used with the method and apparatus of the present invention. The receiver probes 110 and 302, respectively, are both spaced apart a predetermined distance from the transmitter probe 202. In the preferred embodiment, receiver probe 110 and receiver probe 302 are spaced apart from transmitter probe 202 by about one-half to ten feet (0.15 to 3m). Preferably, both receiver probes 110 and 302, respectively, are positioned within the same azimuthal angle as the transmitter probe 202, as illustrated. However, the receiver probes may be positioned at a different azimuthal angle. The first receiver can be at the same depth, but at an 180° azimuthal angle. The receiver probes 110 and 302, respectively, are in contact with the wall of the borehole 102 to isolate the receiver probes 110 and 302, respectively, from the borehole fluids.

[0026] In the second and third embodiments, the tool is operated in the same manner as the tool in the first embodiment but the addition of more than one receiver probe provides additional data especially useful in redundancy analysis. The use of more than one receiver probe also provides additional data especially useful for investigation at various depths within the formation and for determining permeability barriers within the formation. In the case of two receiver probes with varying azimuthal angles, anisotropy with respect the bore hole can be determined.

[0027] As an example, sample results are plotted in Figure 4, wherein the group velocity (C_g) in feet per second (0.3048 ms^{-1}) is plotted on the vertical axis, and the permeability (k) and the center frequency in hertz (Hz) are plotted on the horizontal axes. In the example illustrated in Figure 4, the permeability (k) ranges from 0 md to 1000 md, and the frequency (f) ranges from 0 Hz to 10 Hz, an oscillation rate that is easily sustained mechanically, for example, with a formation tester piston. The example assumes a 20% porosity (φ) formation and water at room temperature and pressure, having a viscosity (μ) of 1 cp (0.001 Pa s) and a compressibility (c) of 3 x $10^6$1/psi (20.67 1/KPa). The velocities are found to be in the range of 10 to 200 feet per second (3 to 61

ms^{-1}) and are easily measurable. As illustrated in Figure 4, the group velocity (C_g) versus the permeability (k) at a fixed center frequency changes approximately parabolically, illustrating that pulsed well transients can be used to resolve low permeability formation properties in a stable manner.

[0028] The method and apparatus of the present invention can be used alone or to augment either the standard drawdown-buildup method or the phase delay method and is advantageous in low permeability formations. One advantage is that problems associated with phase wrapping do not arise. Another advantage is in the use of the first arrival times of a waveform, which are simple to detect. Still another advantage lies in the use of a short duration pulse, wherein the problem of "digging out" or deciphering amplitude information from a mean background field that decays geometrically, is not as severe. The use of a centered frequency excitation also offers the use of a simple formula for determining formation properties.

[0029] While preferred embodiments have been shown and described, various modifications and substitutions may be made thereto without departing from the scope of the accompanying claims. Accordingly it is to be understood that the present invention has been described by way of illustrations and not limitations.

Claims

1. A method of determining properties of a geological formation which method comprises: providing downhole a tool (100; 200; 300) having a pulse generator (114) and at least one receiver probe (110; 302), the or each receiver probe being spaced apart a predetermined distance from the pulse generator; generating a pulsed pressure waveform in the geological formation with the pulse generator, wherein the pulsed pressure waveform is created about a first center frequency; sensing, at a receiver probe, a first arrival time of the pulsed pressure waveform; and determining the velocity of the pulsed pressure waveform.

2. A method according to claim 1, wherein the pulsed pressure waveform is a short duration sinusoidal pressure wave, preferably from four to ten cycles of the first center frequency.

3. A method according to claim 1 or 2, wherein the velocity of the pulsed pressure waveform is used to determine the permeability and/or the porosity of the geological formation and/or the viscosity and/or compressibility of the fluids in the geological formation.

4. A method according to claim 1, 2 or 3 wherein the center frequency is variable and is increased relative to the first center frequency to permit high resolution shallow depths of investigation within the geological formation or decreased relative to the first center frequency to permit deeper depths of investigation within the geological formation.

5. A method according to claim 1, 2, 3 or 4, wherein the center frequency is between one and one hundred Hertz.

6. A geological formation tester tool (100; 200; 300) comprising: a pulse generator (114) for generating a pulsed pressure waveform in a geological formation wherein the pulsed pressure waveform is created about a first center frequency; at least one receiver probe (110; 302), the or each receiver probe being spaced apart a predetermined distance from the pulse generator and in contact with the geological formation; and a sensor (118; 306) operably connected to the or each receiver probe for sensing a first arrival time, at each receiver probe, of the pulsed pressure waveform.

7. A tool according to claim 6, further comprising: a transmitter probe (202) operably connected to the pulse generator (114) for transmitting the pulsed pressure waveform to the geological formation, the transmitter probe being contactable with the geological formation.

8. A tool according to claim 7, wherein the transmitter probe is within the same azimuthal angle as the or each receiver probe (110; 302).

9. A tool according to claim 6, 7 or 8, wherein the pulse generator is a reciprocating piston.

10. A tool according to claim 6, 7, 8 or 9, wherein the pulsed pressure waveform is a short duration sinusoidal pressure wave.

11. A tool according to any of claims 6 to 10, wherein the sensor includes a high accuracy quartz gauge.

12. A tool according to any of claims 6 to 11, further comprising means for determining a velocity of the pulsed pressure waveform and for determining the permeability of the geological formation from the determined velocity, and the pulse generator includes means for varying the center frequency.

13. A tool according to any of claims 6 to 12, wherein the center frequency is between one and one hundred hertz.

14. A tool according to any of claims 6 to 13, wherein the distance between the receiver probe (110; 302) and the pulse generator (114) or transmitter probe

(202) is between one half and ten feet (0.15 to 3m).

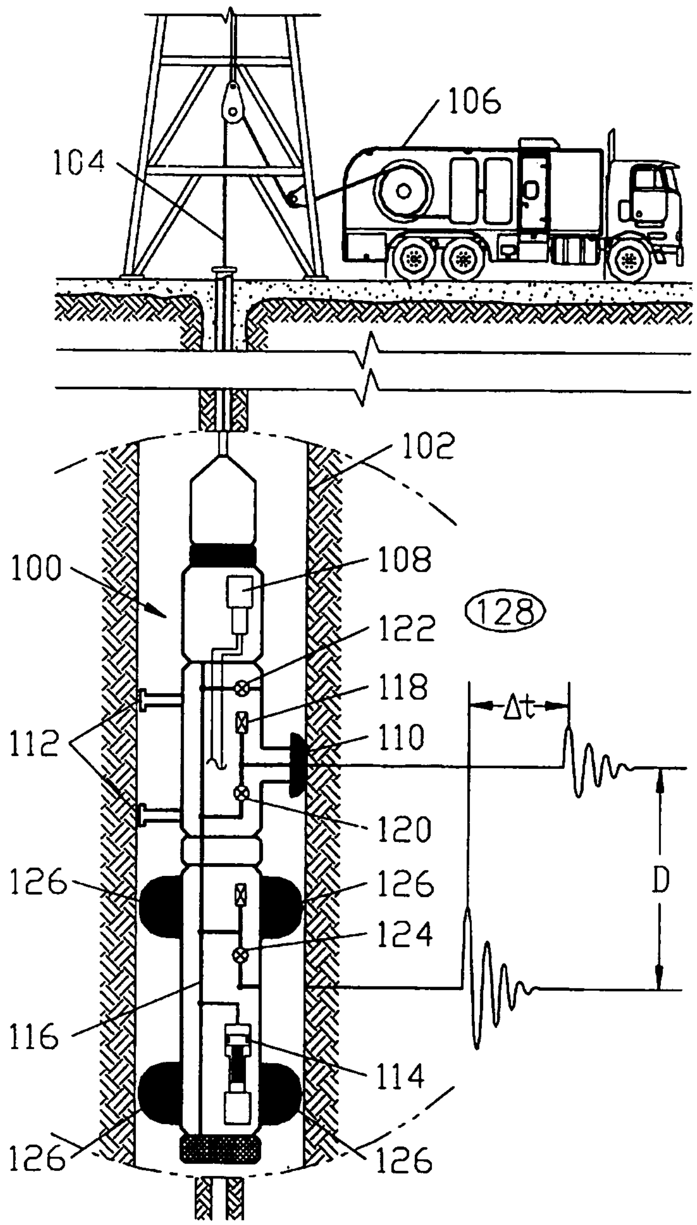

106
104
102
100
108
128
122
118
112
Δt
110
120
126
126
D
124
116
114
126
126

FIG. 1

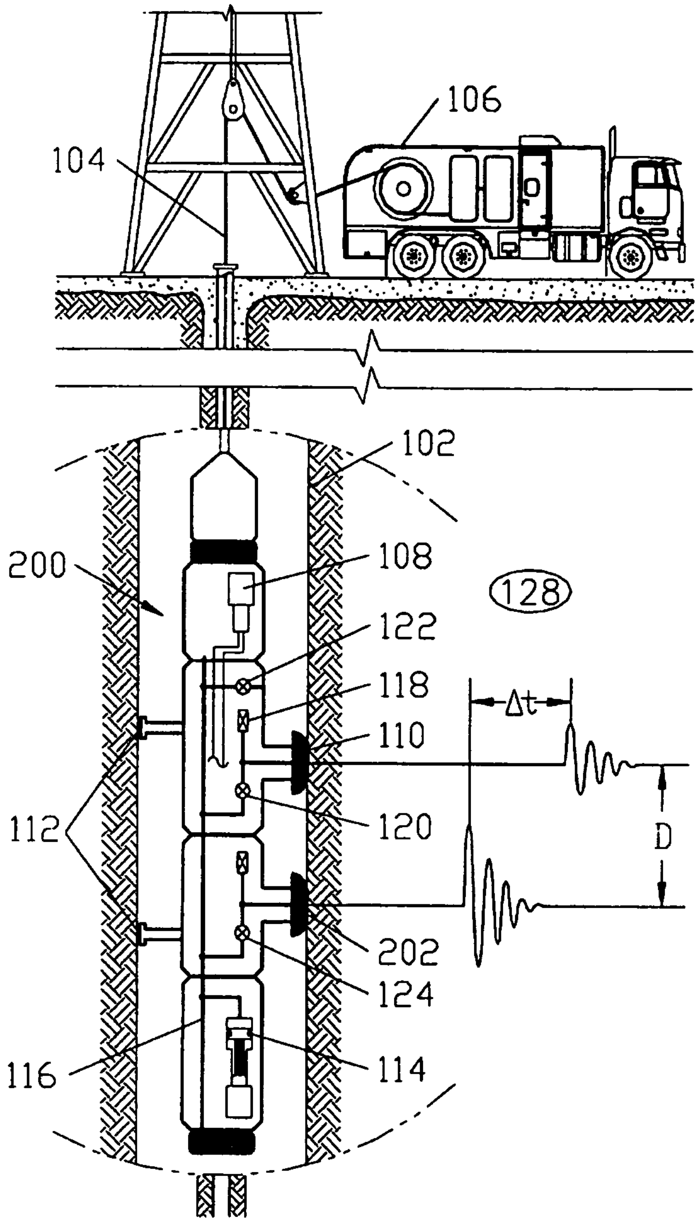


FIG. 2

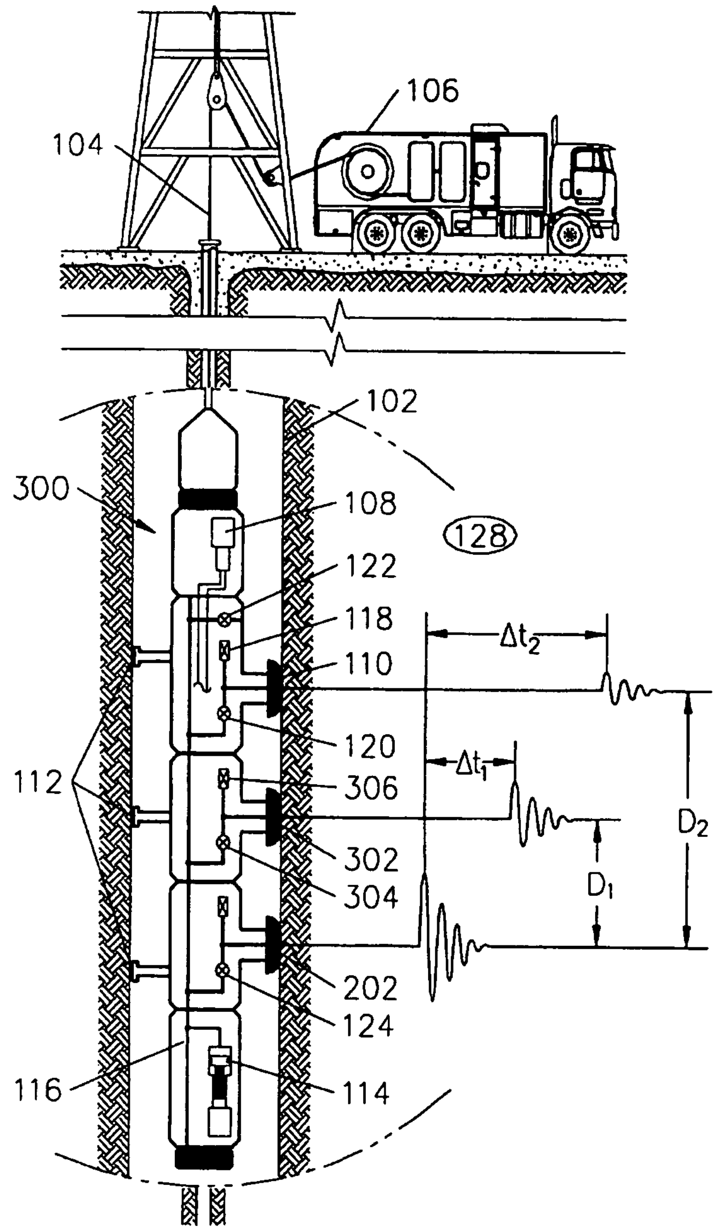
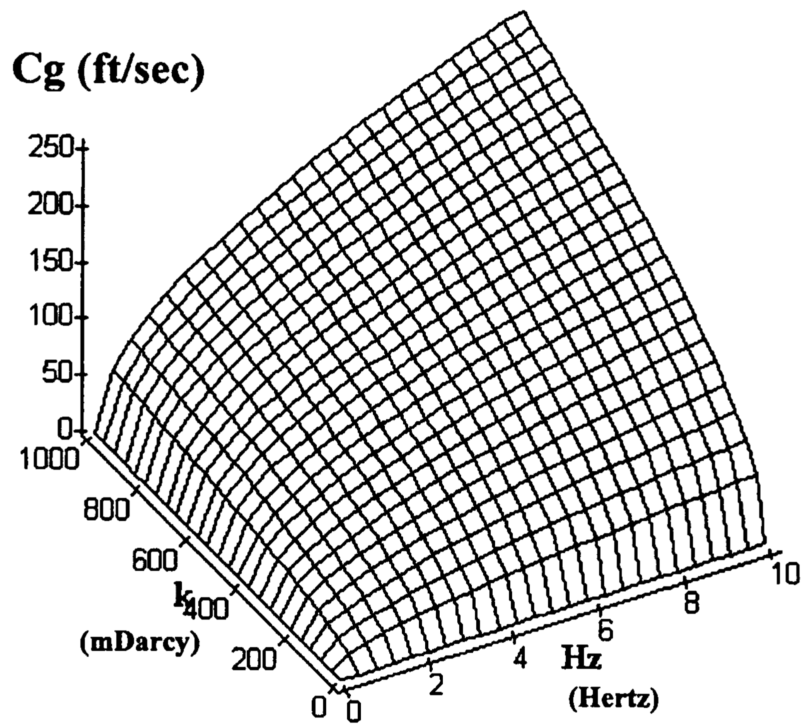

106
104
102
300
108
128
122
118
Δt_2
110
120
Δt_1
112
306
D_2
302
D_1
304
202
124
116
114

FIG. 3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200
150
100
50
0
1000
800
600
k
400
(mDarcy)
200
0
0
2
4
6
8
10
Hz
(Hertz)

FIG. 4